

GSC 07396–00759 = V4046 Sgr C[D]: A WIDE-SEPARATION COMPANION TO THE CLOSE T TAURI BINARY SYSTEM V4046 Sgr AB

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ABSTRACT

We explore the possibility that GSC 07396–00759 (spectral type M1e) is a widely separated (~ 2.82 , or projected separation $\sim 12,350$ AU) companion to the “old” (age ~ 12 Myr) classical T Tauri binary system V4046 Sgr AB, as suggested by the proximity and similar space motions of the two systems. If the two systems are equidistant and coeval, then GSC 07396–00759, like V4046 Sgr AB, must be a spectroscopic binary with nearly equal-mass components, and V4046 Sgr must be at least ~ 8 Myr old. Analysis of a serendipitous *Chandra* X-ray grating spectrum and light curve as well as *XMM-Newton* light curves and CCD spectra of GSC 07396–00759 obtained during long exposures targeting V4046 Sgr AB reveals a relatively hard ($T_X \sim 10^7$ K) X-ray spectrum, strong flaring, and relatively low-density plasma. These X-ray characteristics of GSC 07396–00759 are indicative of a high level of coronal activity, consistent with its apparent weak-lined T Tauri star status. Interactions between V4046 Sgr AB and GSC 07396–00759 when the two systems were more closely bound may be responsible for (1) their dissolution $\sim 10^6$ yr ago, (2) the present tight, circular orbit of V4046 Sgr AB, and (3) the persistence of the gaseous circumbinary disk still orbiting V4046 Sgr AB.

Key words: binaries: close – circumstellar matter – protoplanetary disks – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

Thanks to their proximity, individual members of the various nearby ($D \lesssim 100$ pc), young (age ~ 10 – 70 Myr) stellar groups identified over the past ~ 15 yr (for a recent review, see Zuckerman et al. 2011) provide readily accessible examples of, among other things, the late evolution of protoplanetary disks (e.g., Akeson et al. 2011; Hughes et al. 2011, and references therein) and the early stages of evolution of exoplanetary systems (Marois et al. 2008) and hierarchical binary star systems (Kastner et al. 2008a). In their tests of a method to identify such comoving groups of young stars, Torres et al. (2006) established as a candidate member of the β Pic Moving Group (β PMG) the close binary classical T Tauri system V4046 Sgr ($P \sim 2.4$ days; Stempels & Gahm 2004 and references therein). Via the cluster traceback method, Torres et al. (2008) estimated a distance of only 73 pc to V4046 Sgr. Although the age of the β PMG is estimated to be ~ 12 Myr (Zuckerman & Song 2004 and references therein), the twin members of this fascinating, short-period binary are both evidently still accreting (Stempels & Gahm 2004) from a relatively large and massive circumbinary disk of gas and dust (Kastner et al. 2008b; Rodriguez et al. 2010).

Torres et al. (2006, 2008) also identified, as another β PMG candidate, the star GSC 07396–00759 (hereafter GSC0739,

spectral type M1e or M1.5e; Riaz et al. 2006) on the basis of its proximity to V4046 Sgr (separation 2.82) and the similar radial velocities and similarly large photospheric Li abundances of the two systems (the Li $\lambda 6708$ equivalent widths of V4046 Sgr and GSC0739 are 440 and 200 mÅ, respectively; Riaz et al. 2006; da Silva et al. 2009). Given the low surface density of known β PMG members, it is reasonable to hypothesize that GSC0739 is a distant (projected separation ~ 12.4 kAU) companion to the V4046 Sgr binary, as speculated by Torres et al. (2006). In this respect the relationship of GSC0739 to V4046 Sgr may be very much like that of 2M1235–39 to the well-studied TW Hya Association (TWA) system HR 4796AB (Kastner et al. 2008a), whose primary is a young (β Pic-like) A star with debris disk, or that of the brown dwarf candidate TWA 28 to TW Hya itself (Teixeira et al. 2008).

If GSC0739 and 2M1235–39 (= HR 4796C, the putative tertiary component of HR 4796) are distant companions to the better-studied V4046 Sgr and HR 4796, respectively, then their present orbital periods are $\sim 10\%$ of the (~ 10 Myr) ages of these systems. Hence these objects may offer unique insight into the orbital evolution (and especially the dissolution) of young hierarchical binaries and, perhaps, the likelihood of, and conditions necessary for, formation of planets with circumbinary versus circumstellar orbits.

Table 1
GSC0739: Photometry^a

| <i>B</i> | <i>V</i> | <i>R</i> | <i>I</i> | <i>J</i> | <i>H</i> | <i>K</i> |
|----------|----------|----------|----------|-------------|-------------|-------------|
| 14.14 | 12.78 | 12.13 | 10.64 | 9.44 (0.02) | 8.77 (0.04) | 8.54 (0.02) |

Note. ^a Photometric data compiled from SIMBAD (sources: *Tycho* and UCAC3 catalogs, and Torres et al. 2006). Photometric uncertainties available only for 2MASS data.

Here, we briefly evaluate the available data concerning the space motions of V4046 Sgr and GSC0730, and we analyze optical/IR photometry and serendipitous X-ray observations of GSC0739 (including new *XMM-Newton* X-ray data obtained during the course of a coordinated observing campaign targeting V4046 Sgr; Argiroffi et al. 2011). We use the results to assess the likelihood that GSC0739 is indeed a distant companion to V4046 Sgr and to better ascertain the nature of the former. Finally, we consider the implications if the two systems are (or were) physically bound.

2. DATA, ANALYSIS, AND RESULTS

2.1. Proper Motions and Radial Velocities

The UCAC3 catalog (Zacharias et al. 2010) proper motions (PMs) listed for V4046 Sgr and GSC0739 are $(\mu_\alpha, \mu_\delta) = (+3.3 \pm 1.7, -52.0 \pm 1.3)$ mas yr⁻¹ and $(+1.1 \pm 2.8, -40.0 \pm 13.6)$ mas yr⁻¹, respectively, indicating that (given the UCAC3 measurement errors) the PMs of the two systems are indistinguishable.¹⁴ The heliocentric radial velocities (V_{helio}) of the two systems are also very similar: Torres et al. (2006) list $V_{\text{helio}} = -5.7$ km s⁻¹ for GSC0739, and CO radio line measurements yield $V_{\text{helio}} = -6.2 \pm 0.2$ km s⁻¹ for V4046 Sgr AB (Kastner et al. 2008b; Rodriguez et al. 2010).¹⁵

2.2. Optical/IR SED and Comparison with Pre-MS Tracks

By matching Kurucz model atmospheres (Kurucz 1993) appropriate for late-type main-sequence (MS) stars (i.e., $\log g = 4.5$) to optical/near-IR photometry available in SIMBAD¹⁶ for GSC0739 (Table 1), we deduce a photospheric effective temperature of 3500 ± 100 K, consistent with the M1–1.5 spectral type previously determined for GSC0739 (Torres et al. 2006; Riaz et al. 2006). From the Kurucz model normalization, and assuming the distance to GSC0739 is 73 pc (i.e., GSC0739 and V4046 Sgr are equidistant), we determine a bolometric luminosity $L_{\text{bol}} = 0.15 L_\odot$ (with an approximate uncertainty, dominated by the uncertainty in distance, of $\sim 25\%$). This estimate is consistent with that obtained from the *J* magnitude and *V*–*K* color of GSC0739, $L_{\text{bol}} = 0.17 L_\odot$, following the method described in Kenyon & Hartmann (1995).

We used the foregoing results for GSC0739 and adopted the luminosity and temperature results reported for the individual components of V4046 Sgr AB by Donati et al. (2011) to place these systems on theoretical pre-MS tracks (Figure 1). The comparison illustrates that the two systems can be both

equidistant and coeval only if GSC0739, like V4046 Sgr AB, consists of two components with nearly equal luminosities. Indeed, GSC0739 is flagged as a possible spectroscopic binary by Torres et al. (2006). The positions of the GSC0739 and V4046 Sgr AB systems with respect to the overlaid model evolutionary tracks indicate ages between ~ 10 and ~ 20 Myr, if GSC0739 is a binary. This is consistent with independent (kinematic and pre-MS evolutionary track) age estimates of ~ 12 Myr for the β PMG (see review in Zuckerman & Song 2004). On the other hand, if GSC0739 is single, then Figure 1 indicates that its age is in the range ~ 3 – 10 Myr, i.e., somewhat young for a β PMG member.

2.3. X-Ray Light Curves and Spectra

An off-axis *Chandra*/HETGS gratings spectrum of GSC0739 (total exposure 144.6 ks; ObsIDs 5422, 6265; PI: Herczeg) was serendipitously obtained in 2005 August during an observation targeting V4046 Sgr (Günther et al. 2006). The GSC0739 X-ray spectral data are uncontaminated by V4046 Sgr AB, but the spectral resolution and the exposure of the GSC0739 source are somewhat compromised by its ($\sim 3'$) off-axis position. We extracted and combined the medium-energy grating (MEG) and high-energy grating (HEG) spectra for the full ~ 145 ks exposure duration and generated a light curve covering the first (longer) of the two exposure segments; the resulting light curve and spectrum are displayed in Figure 2. The total (HEG+MEG) count rate, averaged over the entire 144.6 ks exposure duration, was 0.014 counts s⁻¹.

XMM/European Photon Imaging Camera (EPIC) data were serendipitously obtained for GSC0739 in 2009 September, again during an observation (three exposures of ~ 100 ks) targeting V4046 Sgr (Argiroffi et al. 2011). As the source fell along a bad column of EPIC's pn detector, we only analyzed data from the two metal oxide semiconductor (MOS) detectors (the source also fell near the edge of the active area of MOS1, but these data were only slightly compromised). We used the *XMM* Scientific Analysis System (SAS¹⁷ version 10.0.0) to extract MOS1 and MOS2 light curves for the full (~ 5 day) duration of the 3×100 ks exposure (top panel of Figure 3) as well as MOS1 and MOS2 CCD spectra and responses for each individual ~ 100 ks exposure interval (bottom panels of Figure 3). Calibrations were performed using the current calibration files from release note 271, 2010 December 21. Combined MOS1+MOS2 count rates are listed in Table 2.

The *Chandra* and *XMM* light curves reveal strong X-ray flaring at GSC0739. An impulsive flare with amplitude ~ 10 times the quiescent flux level and exponential decay is observed starting at about 65 ks into the first ~ 100 ks segment of the *Chandra* observation (Figure 2, top panel). A flare of similar shape (with amplitude ~ 4 times quiescent) is observed near the beginning of the overall ~ 5 day *XMM* exposure and its decay appears to last the entire duration of the first ~ 100 ks exposure segment; a smaller flare and several small count rate spikes are also seen in the second and third *XMM* exposure segments (Figure 3, top).

Table 2 and Figure 3 (bottom panels) summarize the results of fits of variable-abundance (see below) absorbed two-component thermal plasma models to spectra extracted from the three ~ 100 ks *XMM*/EPIC (MOS) exposure intervals. A similar model fit to *Chandra*/HETGS data (not shown) yields similar results—i.e., a prominent hard component with $T_X \sim 20$ MK and a weaker soft component with $T_X \sim 5$ – 7 MK—despite

¹⁴ The identical PMs listed for the two systems by Torres et al. (2006, their Table 6) both correspond to the *Tycho* catalog PM of V4046 Sgr AB, i.e., $(+2.1 \pm 2.1, -54.5 \pm 2.3)$ mas yr⁻¹; there is no *Tycho* catalog listing for GSC0739.

¹⁵ Recent results from high-resolution optical spectroscopy indicate that the systemic velocity of V4046 Sgr AB may vary by ~ 0.5 km s⁻¹ (Donati et al. 2011).

¹⁶ The SIMBAD database is maintained and operated at CDS, Strasbourg, France.

¹⁷ <http://xmm.esa.int/sas>

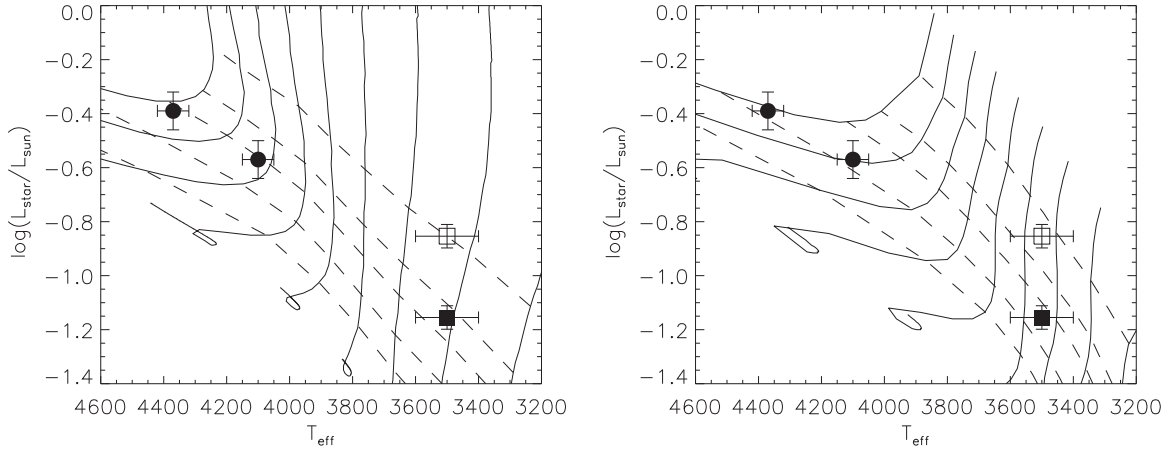


Figure 1. H-R diagram positions of V4046 Sgr AB (circles; luminosity and temperature data from Donati et al. 2011) and GSC0739 (squares; see Section 2.2) overlaid on pre-MS tracks from Siess et al. (2000, left panel) and Baraffe et al. (1998, right panel). The empty square indicates the observed position of GSC0739 and the filled square indicates its position assuming it is a binary system composed of a pair of identical stars. In each panel, the evolutionary tracks (solid lines) correspond to masses ranging from 0.2 to $1.0 M_{\odot}$ (in intervals of $0.1 M_{\odot}$, from right to left), while the isochrones (dashed lines) correspond to ages of 5, 10, 15, 25, and 40 Myr (from top to bottom).

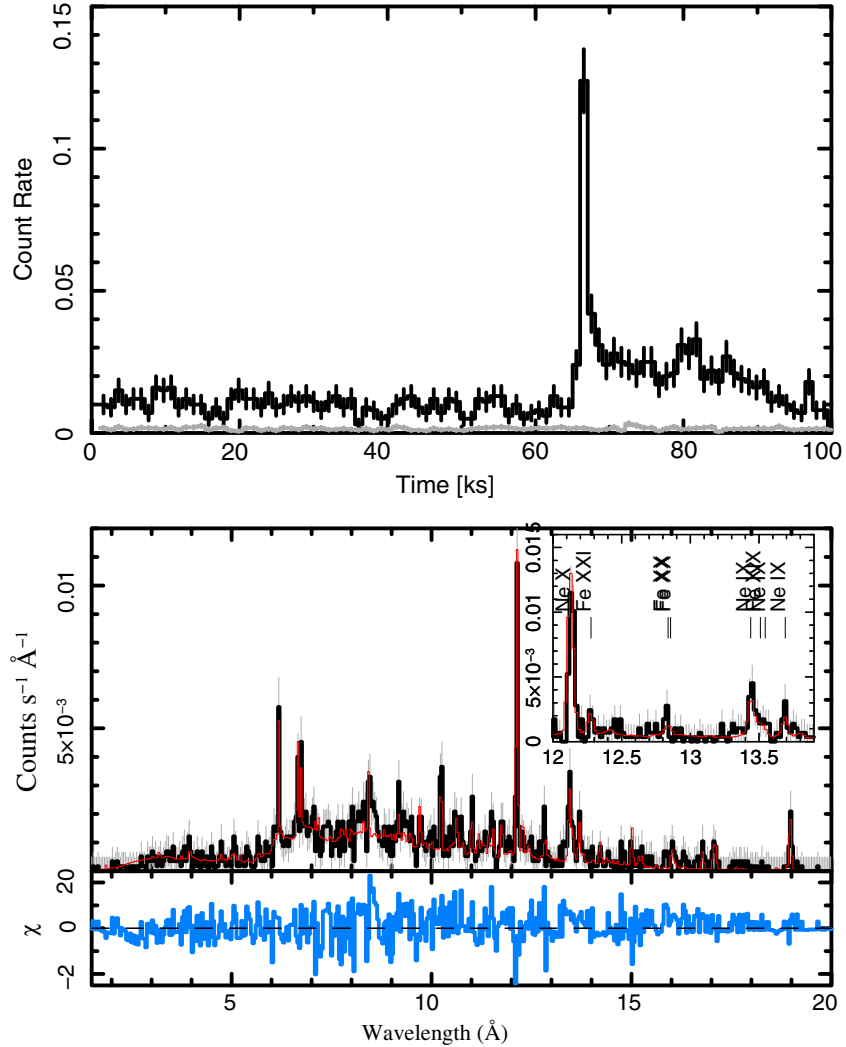


Figure 2. Top: *Chandra*/HETGS light curve of GSC0739, covering the longer (~ 100 ks) continuous observing segment of the two-segment 145 ks exposure. Black: source; gray: background. Bottom: *Chandra*/HETGS spectrum of GSC0739 (black, with gray error bars) overlaid with best-fit APED plasma model (red) in which the emission measure distribution is assumed to follow a power law (see the text). The lower panel shows the residuals of the fit. The inset is a blowup of the 12.0–13.9 Å region, illustrating the strong emission lines of Ne x and Ne ix as well as weak lines of highly ionized Fe.

(A color version of this figure is available in the online journal.)

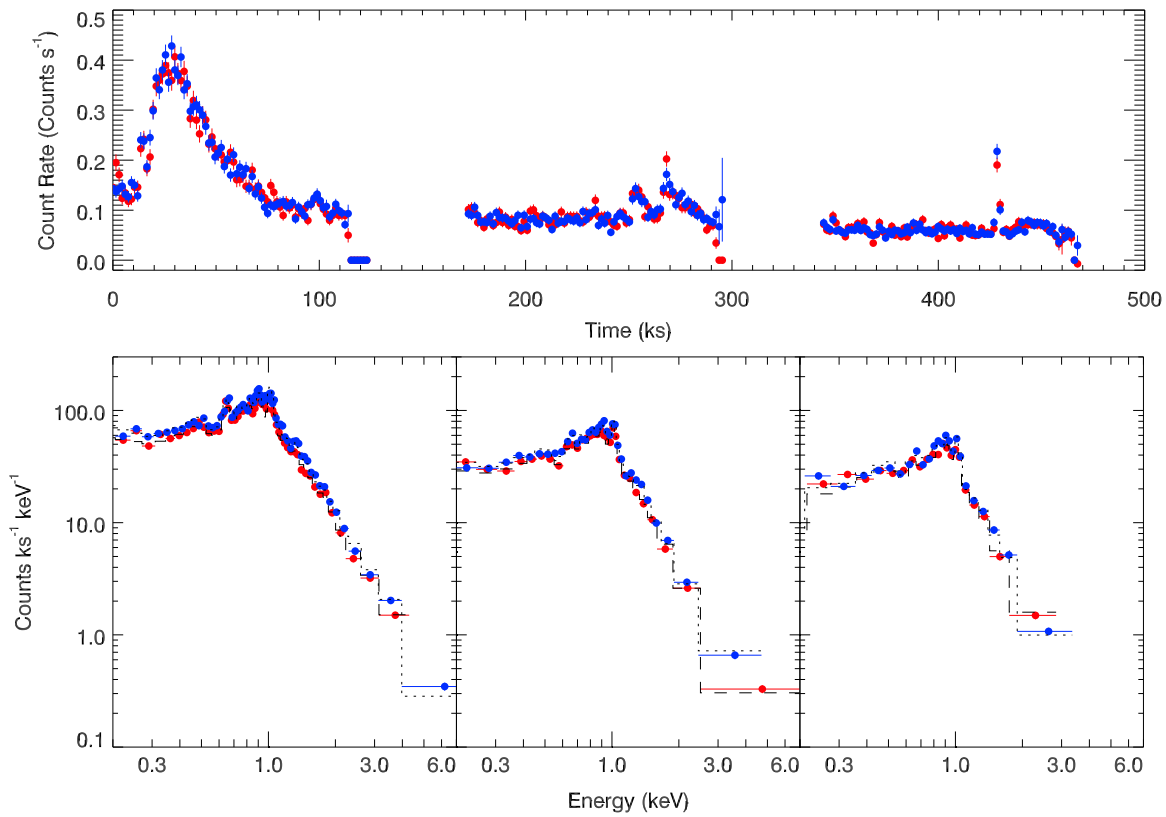


Figure 3. Top: *XMM*/EPIC MOS light curve of GSC0739. Binsize is 1500 s. Bottom: MOS spectra corresponding to the three ~ 100 ks observing intervals illustrated in the light curve in the top panel, with best-fit two-component thermal plasma models overlaid. In all panels, red points indicate MOS1 data and blue points indicate MOS 2 data.

(A color version of this figure is available in the online journal.)

Table 2
GSC0739: *XMM* X-Ray Spectral Fit Results^a

| (Obs. Interval) | C^b (s^{-1}) | N_H (10^{19} cm^{-2}) | T_1 (MK) | EM_1^c (10^{52} cm^{-3}) | T_2 (MK) | EM_2^c (10^{52} cm^{-3}) | L_x ($\text{erg cm}^{-2} \text{ s}^{-1}$) | $\log L_x/L_{\text{bol}}$ |
|-----------------|-----------------------|--|---------------|---|---------------|---|--|---------------------------|
| (1) | 0.24 | 0.0–3.0 | 5.2–5.6 | 3.1–3.3 | 21–23 | 3.3–3.5 | 9.6×10^{29} | –2.76 |
| (2) | 0.12 | 2.0–8.0 | 5.3–5.8 | 2.4–2.6 | 17–20 | 1.1–1.3 | 3.8×10^{29} | –3.17 |
| (3) | 0.081 | 3.0 ^d | 5.2–5.6 | 2.8–3.1 | 14–27 | 0.38–0.6 | 2.9×10^{29} | –3.28 |

Notes.

^a Fit to absorbed two-component, variable-abundance (APED) plasma models, with parameter ranges corresponding to 90% confidence intervals.

^b Combined MOS1+MOS2 count rate.

^c Plasma component emission measure.

^d Parameter fixed during fitting.

the different instrumentation; we conclude that, overall, the plasma physical conditions did not change markedly between 2005 and 2009. Nevertheless, the strong short-term variability of the source is apparent in the *XMM* fit results (Table 2), which indicate a steady decline in the emission measure of the hard component and, possibly, a slight decrease in T_x as the observation progressed and the strong flare faded (the source may have suffered from photon pileup during the first exposure interval).

Individual line intensities in the *Chandra*/HETGS data are not particularly well fit by the foregoing simple (two-component) model, as expected given the continuum of plasma temperatures that is likely present in the X-ray-emitting region. Hence, we performed global fitting of a broken power-law emis-

sion measure distribution model (using *isis*¹⁸ and ATOMDB v2.0¹⁹), such as that used by Rosner et al. (1978) or Peres et al. (2001) for modeling coronal loops, to the gratings data. The model is specified by an emission measure normalization, the peak temperature (T_{peak}), the power-law slopes below (α) and above (β) the peak temperature, and the elemental abundances. The interstellar absorption was assumed to be negligible (a safe assumption given the very modest absorption determined from the fits to *XMM* data; Table 2). To account for the instrumental off-axis line spread function, we used a broadening equivalent to a Gaussian turbulent velocity of 600 km s^{-1} . The resulting best-fit model is overlaid on the *Chandra*/HETGS spectrum

¹⁸ <http://space.mit.edu/cxc/isis/>

¹⁹ <http://www.atomdb.org/>

in Figure 2 (bottom panel); the best-fit model parameters are $T_{\text{peak}} = 11.2 \text{ MK}$ (0.97 keV), $\alpha = 0.2$, $\beta = -1.8$, and an emission measure of $3.3 \times 10^{52} \text{ cm}^{-3}$. The best-fit abundance ratios (relative to solar) are $\text{Ne/O} = 1.8$, $\text{Mg/O} = 0.27$, $\text{Si/O} = 0.6$, and $\text{Fe/O} = 0.27$ (the two-component plasma model fits to the *XMM*/MOS data also indicate an elevated Ne/O ratio and depressed Fe/O ratio). These Ne/O and Fe/O ratios are typical of coronally active stars (see review in Testa 2010). Analysis of X-ray gratings spectra of V4046 Sgr AB likewise indicates enhanced Ne/O and low Fe/O, although the Ne/O enhancement is more extreme (a factor ~ 5 larger than solar; Günther et al. 2006) in the case of this (actively accreting) system.

Although the resolution of the *Chandra*/HETGS spectrum of GSC0739 suffers from degradation due to the off-axis position of the source, it is apparent that the forbidden to intercombination line ratio within the He-like Ne ix line complex (at $\sim 13.5 \text{ \AA}$) is large (Figure 2, inset in the bottom panel), indicative of lower-density ($\lesssim 10^{10} \text{ cm}^{-3}$) plasma. Figure 2 (bottom panel) also illustrates the relatively large Ne x to Ne ix line ratios of GSC0739, reflecting the dominance of relatively hot ($\gtrsim 10 \text{ MK}$) plasma in its emission measure distribution (Table 2). These density- and temperature-sensitive Ne line ratios are consistent with coronal X-ray emission and, hence, a weak-lined T Tauri classification for this source (see, e.g., Kastner et al. 2004; Huenemoerder et al. 2007). Both Ne line spectral diagnostics also stand in stark contrast to those of V4046 Sgr AB; the latter displays Ne (and O) line ratios indicative of a significant emission contribution from cooler ($\sim 3 \text{ MK}$) plasma at much higher density ($\sim 10^{12} \text{ cm}^{-3}$; Günther et al. 2006; Argiroffi et al. 2011), as expected if much of the X-ray emission (essentially, all of the soft component) is generated in accretion shocks (Sacco et al. 2010 and references therein).

3. DISCUSSION AND CONCLUSIONS

The available PM and radial velocity data (Section 2.1) support the hypothesis that V4046 Sgr AB and GSC0739 are comoving systems. Hence—provided GSC0739 is also a close binary (Section 3.2)—the two systems likely constitute a hierarchical multiple and, in the following, we refer to GSC0739 as V4046 Sgr C[D].

3.1. The Nature of V4046 Sgr C[D]

Based on its lack of $\text{H}\alpha$ emission ($\text{H}\alpha$ equivalent width of $+3.1 \text{ \AA}$; Riaz et al. 2006), V4046 Sgr C[D] appears to be best classified as a weak-lined T Tauri system (wTTS); i.e., unlike V4046 Sgr AB, the system shows no evidence for ongoing accretion. The prominent hard ($T_X \sim 10^7 \text{ K}$) X-ray spectral component, strong X-ray flaring, and relatively low-density X-ray-emitting plasma of V4046 Sgr C[D] (Section 2.3)—all of which are indicative of a high level of coronal activity—are fully consistent with such a wTTS classification.

3.2. V4046 Sgr AB and C[D]: Constraints on System Age and Origin

If the V4046 Sgr AB and C[D] systems are indeed bound, they are only weakly so, given their very large projected separation of $\sim 12,350 \text{ AU}$ (assuming $D = 73 \text{ pc}$). Assuming the systems are still bound, the orbital period of V4046 Sgr C[D] with respect to V4046 Sgr AB would be of order $\sim 10^6 \text{ yr}$, i.e., a significant fraction of their estimated ages. This system would therefore appear to be the most loosely bound hierarchical

binary system known in the βPMG . However, two similarly loosely bound binaries have been identified thus far in the TWA: TWA 11AB and TWA 11C, projected separation $\sim 13,500 \text{ AU}$ (Kastner et al. 2008a), and TW Hya (TWA 1) and TWA 28, projected separation $\sim 41,000 \text{ AU}$ (Teixeira et al. 2008). The separations of these nearby, young hierarchical multiple systems are comparable to those of the most loosely bound binaries in the solar neighborhood (the separation distribution of nearby field binaries appears to be truncated at $\sim 20,000 \text{ AU}$; Close et al. 1990). The (very low mass) TWA 30A and 30B star/disk systems, which are separated on the sky by $\sim 3400 \text{ AU}$ (Looper et al. 2010), are also very weakly bound.

However, the analysis in Section 2.2 strongly implies that V4046 Sgr AB and the putative V4046 Sgr C[D] could only be coeval if the latter, like the former, is a nearly equal component binary—consistent with previous suspicions concerning this system (Torres et al. 2006). Furthermore, if the two systems indeed formed together, then the position of V4046 Sgr C[D] in Figure 1 appears to place a conservative lower limit of $\sim 8 \text{ Myr}$ on the age of the V4046 Sgr multiple system, while—on the basis of this comparison of V4046 Sgr C[D] with pre-MS tracks alone, and given the present uncertainties in the stellar parameters—the system may be as old as $\sim 25 \text{ Myr}$.

Numerical simulations of hierarchical triple star systems demonstrate that the action of Kozai oscillations, in combination with tidal friction, shrinks and circularizes the orbit of the inner binary (Fabrycky & Tremaine 2007). Although Fabrycky & Tremaine (2007) find that the fraction of circularized, close (few-day period) binaries with tertiaries as distant as V4046 Sgr C[D] should be negligibly small, they also note that $\sim 40\%$ of hierarchical triple systems are “lost” from their numerical sample due to dissolution. Perhaps V4046 Sgr AB and C[D] constitute such a (recently dissolved) hierarchical multiple system that, at a slightly earlier epoch, resembled closer, young hierarchical binaries (such as the $\sim 8 \text{ Myr}$ old TWA systems HD 98800 and Hen 3-600). If so, the dissolution of V4046 Sgr AB and C[D] evidently occurred $\sim 10^6 \text{ yr}$ ago and left behind a close binary with a nearly circular orbit (V4046 Sgr AB has an eccentricity $e < 0.01$; Stempels & Gahm 2004).

Given that V4046 Sgr has apparently well outlived the “canonical” few-Myr timescale for Jovian planet formation (e.g., Currie et al. 2009 and references therein), one might further speculate that the presence of V4046 Sgr C[D] may explain the longevity of the circumbinary disk around V4046 Sgr AB—just as the hierarchical natures of the young multiple systems HD 98800 and Hen 3-600 may explain the persistence and observed properties of the circumbinary dust disk in each of these systems (see, e.g., Prato et al. 2001; Furlan et al. 2007; Andrews et al. 2010, and references therein). Although the details in all of these examples remain to be worked out, in the specific case of V4046 Sgr it is possible that dynamical interactions with component(s) C[D] may have inhibited the formation of gas giant and ice giant planets in circumbinary orbits around components AB, thereby preserving the gaseous, circumbinary disk from which this close binary system is still accreting.

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